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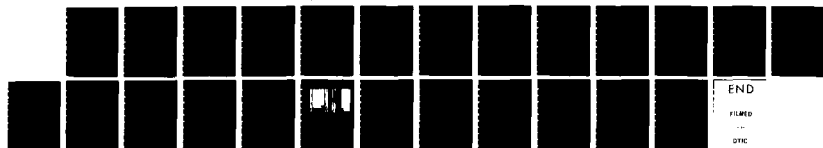
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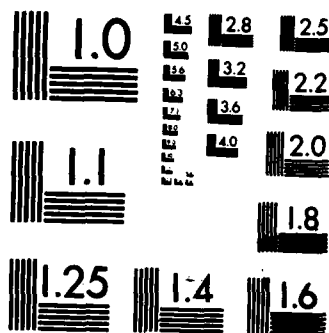
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DC Partial-Discharge/Environmental Test Screening of Space TWTs

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4 June 1984

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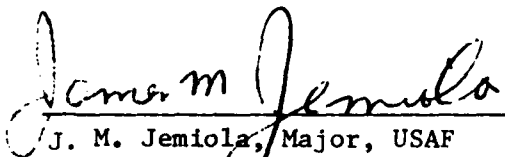
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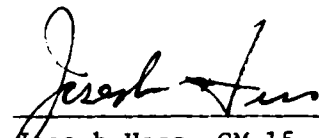
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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.


J. M. Jemiola, Major, USAF
Project Officer


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systems is enhanced by combining dc partial discharge testing with environmental (temperature and pressure) testing. These defects are usually caused by high stresses in the potting produced during temperature excursions by the difference in thermal expansion between the potting material and the confining ceramic-metal structure. Test of a potted TWT with a unique high-voltage problem, as well as tests of many TWTs and TWT analogs with a generic defect, are described. Tests of all-ceramic-insulated TWTs indicate that the high-voltage problem is internal to the vacuum envelope and requires both leakage and discharge measurements for diagnosis. This problem appears to be field emission from contaminated surfaces.

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CONTENTS

I.	INTRODUCTION.....	5
II.	HIGH-VOLTAGE INSULATION SYSTEMS FOR SPACE TWTs.....	9
	A. TWT with External Polymer Potting.....	9
	B. TWT with Ceramic Feedthroughs.....	18
III.	CONCLUSION.....	21
	REFERENCES.....	23



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FIGURES

1.	Traveling Wave Tube and High Voltage Circuit.....	7
2.	Aerospace Partial Discharge/Environmental Test System.....	7
3.	Temperature Profile and Partial-Discharge Signature for Gun Section of Serial No. 301.....	11
4.	Original and Stress-Relieved Design of 293H TWT Collector.....	13
5.	Partial-Discharge Activity in PRAM Collector, Serial No. 034.....	16
6.	HEDD PRAM Collector, Serial No. 036. (a) cut shows the crack between the collector and can (Fig. 4a), (b) close-up of view (a).....	17
7.	Fowler-Nordheim Presentation of I-V Data for Serial No. 015.....	20

TABLE

1.	Summary of Test Results for 293H TWT Collector Analogs.....	15
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I. INTRODUCTION

A critical device used in high-power, wide-bandwidth satellite communication is the traveling-wave tube (TWT). This vacuum tube device consists of an electron gun (cathode and anode) producing an electron beam, a slow-wave structure in the form of a helix surrounded by magnets used for beam focusing, and a beam collector of one or more stages as shown in Fig. 1. In operation, the rf signal to be amplified is impressed on the helix at the input end of the tube and takes the form of a wave traveling on the helix. Interaction between this wave and the electron beam results in an amplified signal at the output end of the tube. For operation of this device, high voltages provided by a suitably designed power supply must be impressed on the cathode, anode, and collectors as indicated in Fig. 1. Isolation of these TWT elements at high voltage (HV) inside the vacuum tube envelope is achieved through the use of ceramic insulators. HV isolation outside the tube is achieved by using either all-ceramic or a combination of ceramic and polymeric insulation.

Communication satellites are being designed to operate for periods up to 10 years. Being an essential part of these systems, the TWTs must also operate reliably during this period in a vacuum environment, undergoing diurnal and annual temperature variations at relatively high temperature during operation and at low temperatures during storage. To ensure long-term reliable operation in a space environment, at least from the standpoint of the integrity of the HV insulation, the TWT must be free of HV defects during ground acceptance testing. To fulfill this requirement, dc partial discharge/environmental testing is being conducted on space TWTs to screen out advanced or incipient defects.

The partial discharge test (PDT) is a recognized HV test technique (Refs. 1 and 2) and consists essentially of applying high voltage to the insulation system under test and monitoring this system for discharges as indicated in Fig. 2. These discharges are measured in terms of the magnitude of electrical charge transfer (in picocoulombs) and frequency. In the test of the HV insulation of the TWT, dc partial discharge testing rather than ac

testing is being used to prevent initiation of extraneous ac material degradation modes. In operation as indicated in Fig. 1, the TWT sees only dc high voltages.

In the TWT test arrangement assembled in the Materials Sciences Laboratory of The Aerospace Corporation, the PDT system is combined with a thermal-vacuum test system so that the TWT can be examined in a simulated operational space environment as shown in Fig. 2. This system is capable of monitoring discharges of magnitudes from 0.25 pC to above 0.25 μ C, a charge range covering discharges in polymeric potting defects that grow from the incipient to the failure stage at operating voltage levels. The temperature and pressure capabilities of this system are -10°C to $+85^{\circ}\text{C}$ and atmospheric pressure to below 10^{-4} Torr, respectively. Long-term repetitive thermal cycling can be performed with the discharge test data automatically processed, recorded, and displayed. The operation of this combined test system was previously described in detail (Ref. 3). The advantages gained by coupling the dc partial discharge test technique to environmental (pressure and temperature) testing, particularly in the test of polymeric potted systems, are discussed in Section II.

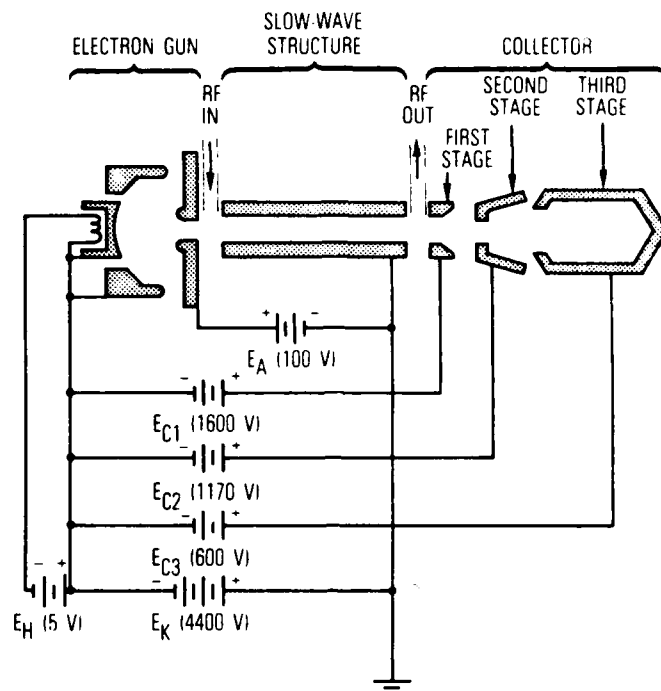


Fig. 1. Traveling Wave Tube and High Voltage Circuit

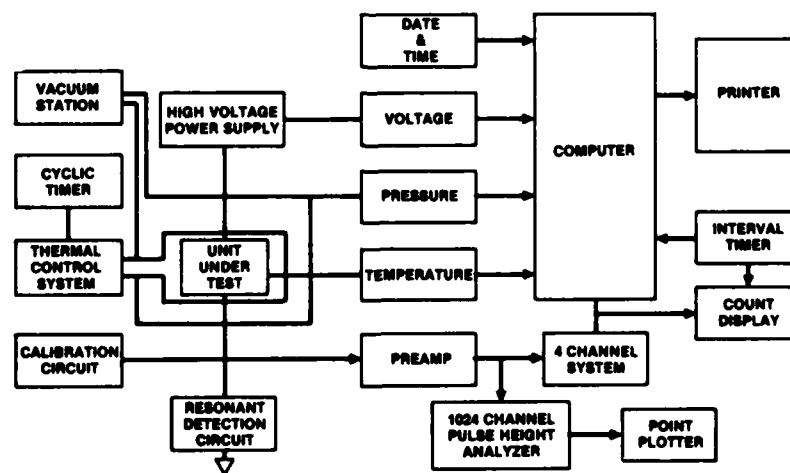


Fig. 2. Aerospace Partial Discharge/Environmental Test System

II. HIGH-VOLTAGE INSULATION SYSTEMS FOR SPACE TWTs

The HV insulation system of two types of TWTs are under examination, using the dc partial discharge/environmental test system. The first type, examined earlier, has an oxide cathode and polymeric potting for HV insulation outside the ceramic-metal vacuum envelope. The second type, examined recently, has a dispenser cathode and ceramic feedthroughs for external insulation. Both types use ceramic-vacuum insulation inside for HV isolation. Early tests of a large number of TWTs and TWT section analogs of the first type, and recent tests of several TWTs of the second type, have revealed, as expected, quite different partial discharge signatures corresponding to different HV defects and to different degradation and failure modes, the latter observations shown in destructive physical analysis (DPA). These PDT and DPA results are given below.

A. TWT WITH EXTERNAL POLYMER POTTING

In this type of TWT, high voltages at the correct level are brought to the tube by insulated wires. The ends of the wires are attached to the proper electrodes in both the gun and collector end of the tube outside the vacuum envelope. Both ends of the tube are then potted, covering and insulating both the wire attachment points and the outside surfaces of the HV electrodes. This HV polymeric potting, if properly applied to a well-designed TWT, should be free of defects and should enable the TWT to operate reliably at all pressures for extended periods.

The partial discharge signature for a well-potted TWT section (gun or collector) is not discharge-free but shows only low magnitude (< 25 pC) low frequency discharges. Furthermore, these discharges do not increase in magnitude and frequency with thermal cycling in vacuum over extended periods (several days to several weeks at the rate of three thermal cycles per day). These discharges are probably caused by minor defects that do not grow or propagate and should not lead to failure of the TWT.

The partial discharge signature for a TWT section with a major HV defect, in contrast, shows a quite different variation. If the HV defect is at the latent or incipient stage, the associated discharges grow in magnitude and frequency with thermal cycling in vacuum. However, after extended thermal cycling, these discharges may stabilize and not increase to failure levels ($< 0.25 \mu\text{C}$). This stabilization is seen in the discharge signature for the gun section of the Hughes Aircraft Company Electron Dynamics Division (HEDD) TWT Model 293H shown in Fig. 3. In this figure, only discharges above 25 pC are indicated. The frequency of these discharges in the range from 25 pC to 2.5 nC appears to vary with temperature, except at the highest test temperature ($> 80^\circ\text{C}$) near the potting cure temperature (85°C). This variation is consistent with analysis that predicts that the frequency of discharges occurring in cracks and voids under dc electrical stress is proportional to the conductivity of the potting material (Ref. 4) and with potting conductivity that increases with temperature. (The physical reason for this dependency is that, after a discharge, sufficient charge must be conducted again to the discharge site through the potting before another discharge can occur.) A possible explanation for the disappearance of discharges near the potting cure temperature is given below. If the HV defect is at the advanced or failure stage, the discharges are high in magnitude and the low discharge frequencies do not follow temperature. These high magnitude discharges usually occur only in vacuum.

A major HV defect may occur in only one unit of a TWT model series, or the HV defect may be generic, occurring in all units of the series. An example of a single-unit defect is the HV problem found in the gun section of the HEDD 293HA TWT (serial no. 102). This HV defect exhibited, during gun-section test, sporadic high-magnitude discharges in vacuum and continuous discharge activity at intermediate pressures (10^{-2} to 10^{-1} Torr). Outside the TWT, arcing was seen between the collector wire and the TWT cover at these pressures. DPA of the gun section of serial no. 102 showed the defect to be breakdown occurring along the collector wire caused by (1) poor bonding between the collector wire insulation and the Adiprene potting, and (2) routing of the collector wire too close to the HV cathode. Poor bonding was

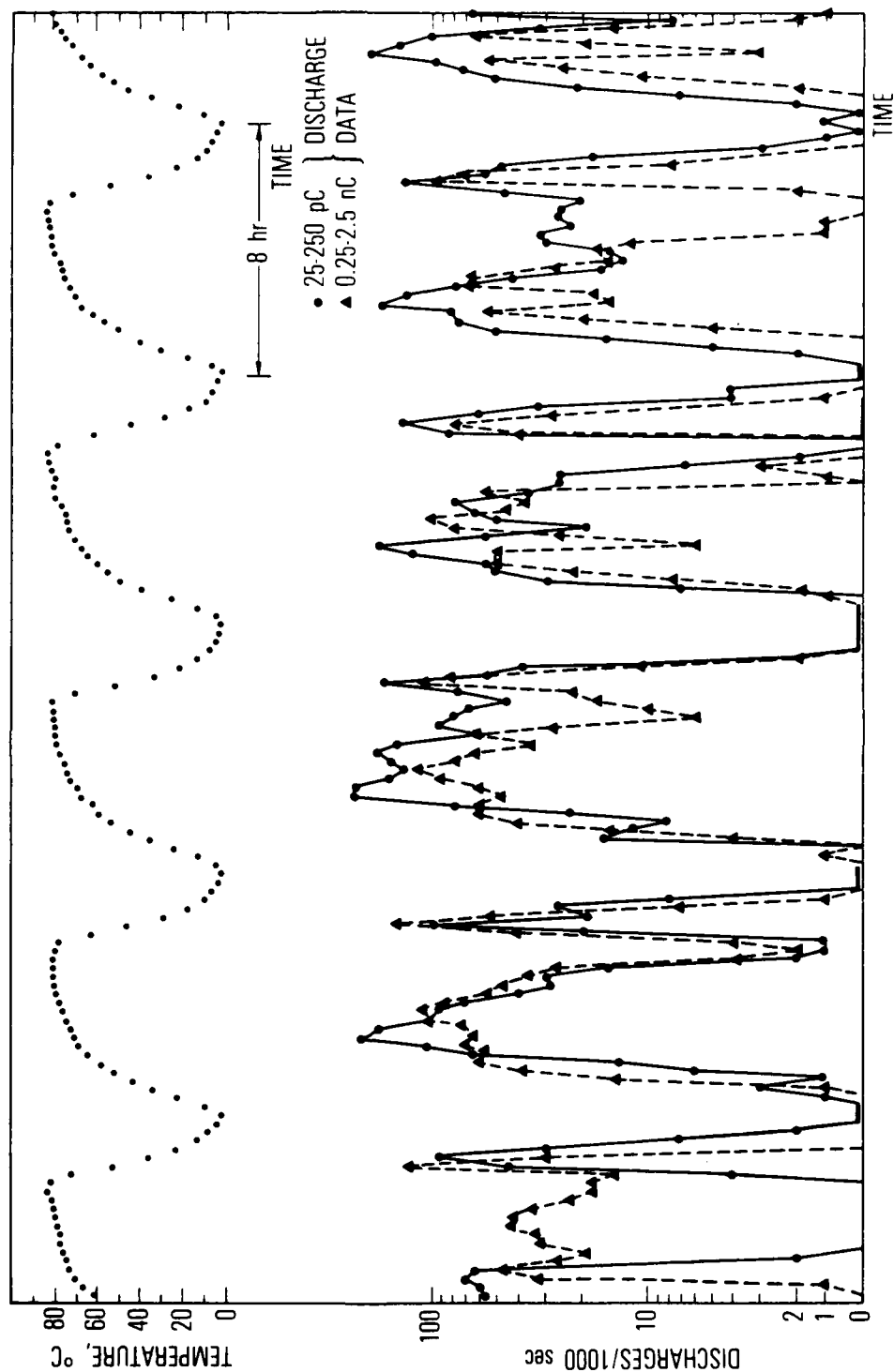


Fig. 3. Temperature Profile and Partial-Discharge Signature for Gun Section of Serial No. 301

attributed to the omission of etching along the length of Teflon-insulated collector wire running through the gun section potting. This example indicates the importance of testing potted insulation at vacuum and intermediate pressures where the electrical stress necessary for breakdown in cracks and voids is minimum, as indicated by the Paschen law for gas ionization breakdown (Ref. 4).

An example of a HV defect that affected all units of a series is the generic design defect found in the collector section of the HEDD 293H TWT. The structural design of this collector section is shown in Fig. 4. HV acceptance tests of these 293H TWTs resulted in numerous failures of the collector sections. Partial discharge tests of several of these TWTs showed failure level ($> 0.25 \mu\text{C}$) discharges occurring usually in vacuum. DPA of these failed units revealed cracks in the bulk potting and separations at the potting and ceramic-metal interfaces in the volume of potting bounded by the collector, the can, and the beryllium oxide insulators shown in Fig. 4. Finite-element thermomechanical stress analysis of this annular section of potting, first by Aerospace (Ref. 5) and then by HEDD and General Electric (Ref. 6), showed that the cracks and separations were caused by high stresses in the Adiprene potting, resulting basically from the difference in thermal expansion between the potting and the ceramic-metal structure. The Adiprene potting is poured and cured at high temperature (85°C) and is essentially stress-free at this temperature. It is also bonded on all sides to the structure. However, as the collector cools to room temperature or to low operational temperature, the potting relative to the structure tries to contract, but being bonded to all sides cannot, thereby producing stresses that exceed the strength of the potting and the interface bonds and, consequently, leading to the cracks and separations.

To correct this problem, several approaches were proposed: (1) replace the high-temperature-cured Adiprene with Uralane, a polyurethane curable at room temperature, and then cure the Uralane at room temperature to minimize the temperature excursions expected during operation and tests, thereby minimizing the stresses in the potting; (2) redesign the collector section of the 293H TWT to eliminate total confinement of the potting, thereby reducing the

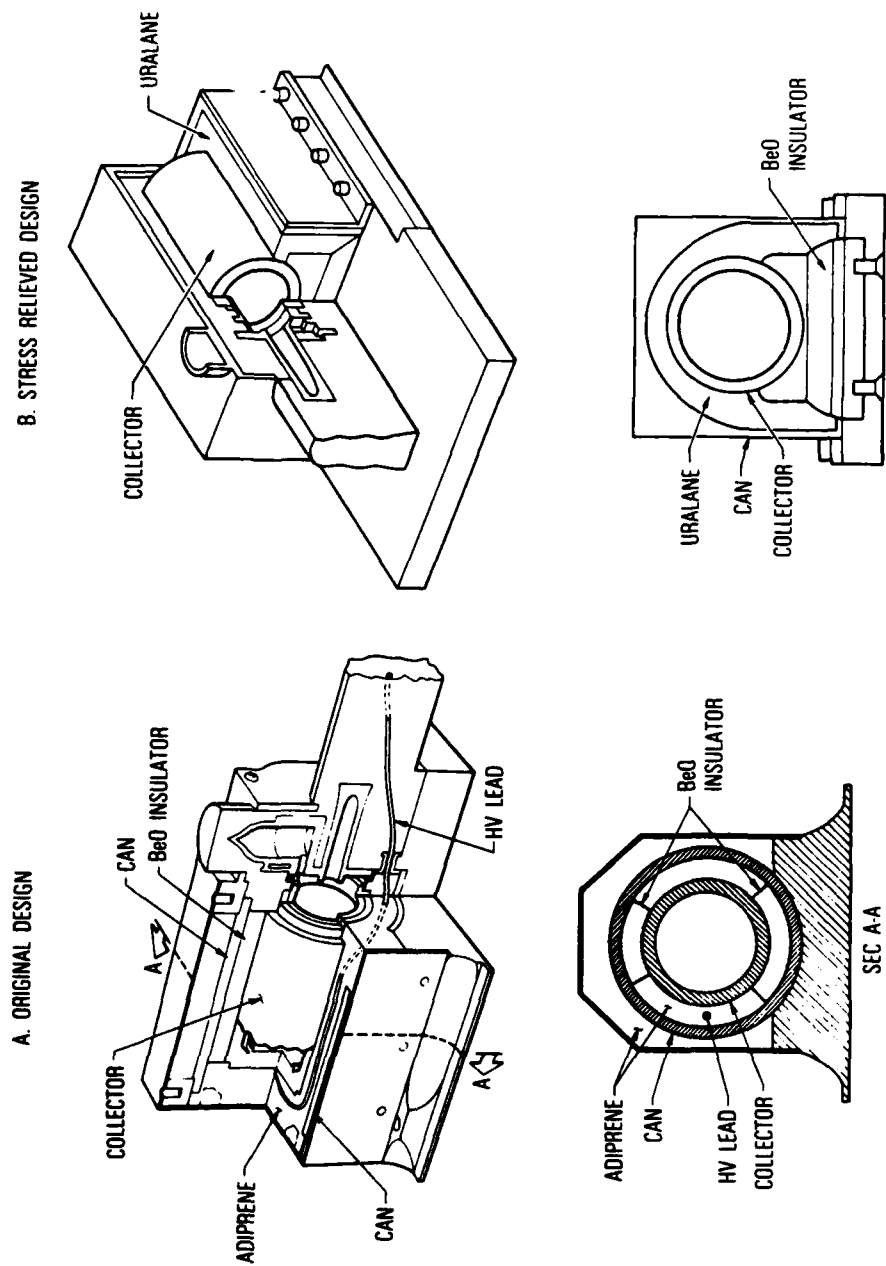


Fig. 4. Original and Stress-Relieved Design of 293H TWT Collector

stresses in the potting. The redesigned collector section providing stress relief is shown in Fig. 4. These approaches were confirmed by stress analysis (Ref. 6). To support the results of these analyses, several groups of 293H TWT collector section analogs were fabricated under the HEDD PRAM program (an Air Force manufacturing technology program) and then subjected to long-term partial discharge/environmental testing at Aerospace. These groups are listed in Table 1 along with a summary of the PDT and DPA results.

All three collector analogs of the original design and material cured at 85°C failed, showing failure-level discharge activity primarily on the cool-down sides of the thermal cycles below room temperature. This action suggests that stresses in the potting are at their maxima (leading to opening of cracks and separations) when the excursions from the cure temperature (85°C) are largest and at their minima (leading to closing of cracks and separations) when the excursions are negligible. These latter changes may account for the disappearance of discharge activity at temperatures above 80°C shown in Fig. 3. (The gun section of serial no. 301 was potted with Adiprene cured at 85°C.)

All the analogs in group 2 were potted with Uralane. Subgroup A showed the least discharge activity with thermal cycling in vacuum. This subgroup had the benefits of both partial stress relief through modification of the original structure and potting cured at room temperature. Subgroup B showed somewhat higher discharge activity but no failures. A representative plot for this subgroup of discharge magnitude at a given temperature versus the number of thermal cycles is given in Fig. 5. This plot shows the appearance of relatively high magnitude discharges, first appearing at low temperatures but gradually occurring at all temperatures. Variations similar to these were observed in the tests of other analogs from subgroups A and B. However, similar plots from tests of subgroup C show immediate appearances of discharges in the charge range (25 pC to 25 nC) over the entire test temperature range (-10°C to 85°C). In subgroup C, one analog failed; the failure site is shown in Fig. 6.

Table 1. Summary of Test Results for 293H TWT Collector Analogs

Group	Design	Material (alumina- filled)	Cure Temperature (°C)	Number of Units	PDT Results	DPA Results
1	Original	Adiprene	85	3	Moderate PD activity All 3 units failed in temp/vac cycling	Cracks and separation Failure site found (S/N 006)
2A	Original (modified)	Uralane	RT + 4 hr at 85	3	Low to moderate activity No failures	Cracks and separations (S/N 019)
2B	Original	Uralane	RT	3	Moderate activity < 25 nC No failures	Cracks and separations (S/N 033)
2C	Original	Uralane	RT + 4 hr at 85	3	Moderate to failure- level activity 1 unit failed	Cracks and separations Failure site found (S/N 036)
3	Redesign (stress relieved)	Uralane	RT	2	Low activity No failure	No DPA performed

RT = room temperature

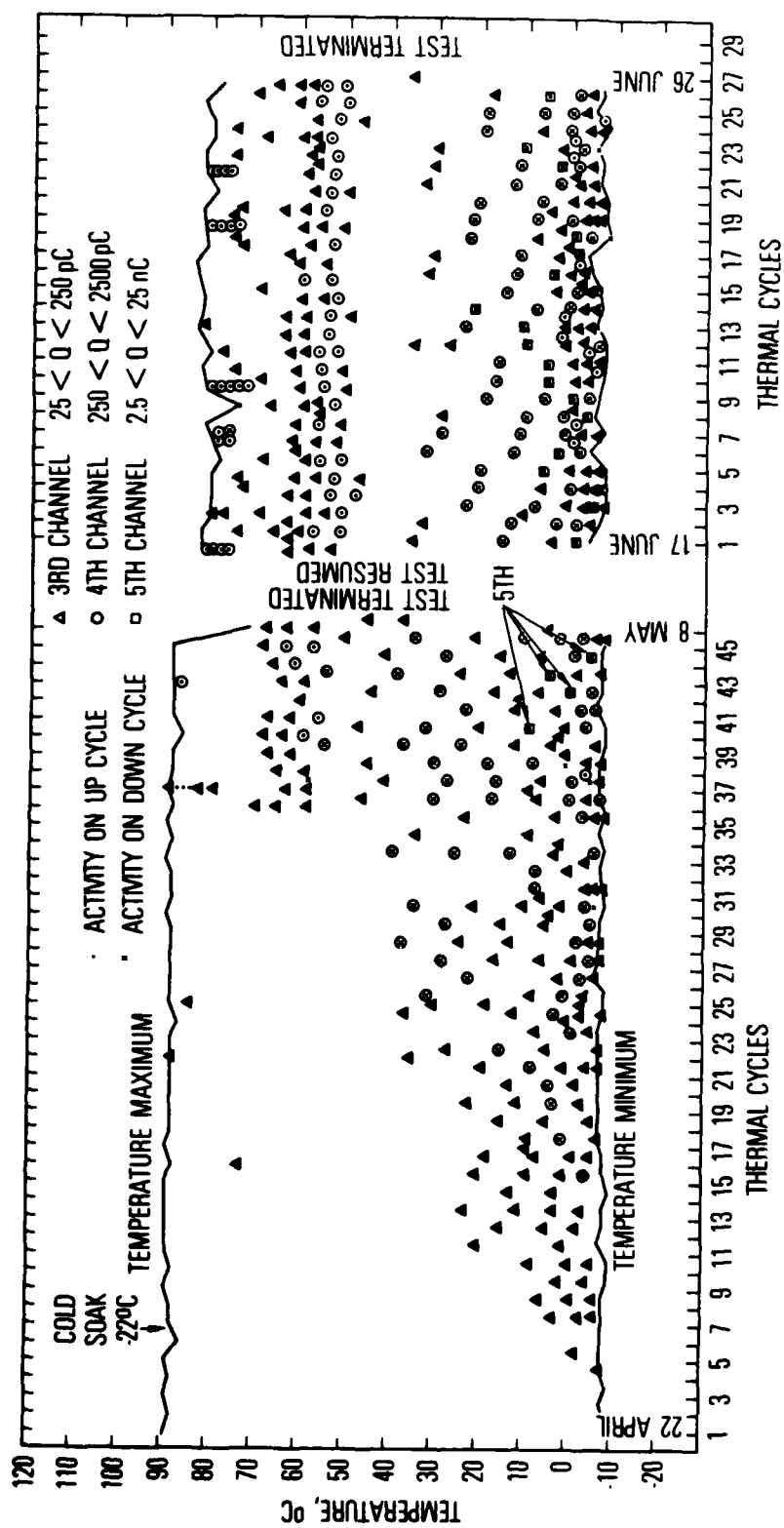


Fig. 5. Partial Discharge Activity in PRAM Collector, Serial No. 034



(a)



(b)

Fig. 6. HEDD PRAM Collector, Serial No. 036. (a) cut shows the crack between the collector and can (Fig. 4a), (b) close-up of view (a)

Tests of analogs from group 3 showed only low magnitude (< 25 pC) and low frequency (< 10 discharges/thermal cycle for discharges above 2.5 pC) discharges, indicating a substantial decrease in discharge activity relative to groups 1 and 2. Therefore, the study summarized in Table 1 supports the analytical prediction that the HV integrity of the 293H collectors can be improved by stress relief and use of potting cured at room temperature.

B. TWT WITH CERAMIC FEEDTHROUGHS

High voltages for this type of TWT are also supplied by insulated wires. The ends of the wires are attached to the external metal terminals of the feedthroughs on both the gun and collector end of the TWT. These TWTs can operate at atmospheric pressure and in vacuum ($< 10^{-3}$ Torr) but not at intermediate pressures without encapsulation of the exposed metal terminals. The TWTs of this type tested to date at Aerospace do not have encapsulated terminals. The ceramic surfaces of these feedthroughs without any encapsulating potting are easily cleaned and, consequently, have not shown any HV breakdown problem.

Low voltages (~ 100 V) current measurements using an electrometer indicate leakage currents in the gun section of the HEDD 289HM TWT (serial no. 015) ranging from 10^{-8} to 10^{-11} A, corresponding to resistances of 10^{10} to 10^{13} ohms for various test configurations. The anode-to-ground resistance is about 10^{10} ohms, whereas the cathode-to-ground resistance is about 10^{13} ohms. The low anode-to-ground resistance was attributed to contamination from laser welding of the gun structure and from uncontrolled getter activation. Similar low-voltage measurements were made on the three-stage collector of serial no. 015. The resistances monitored range from 10^{12} to 10^{14} ohms. The cause of these reduced resistances is unknown. Both gun and collector leakage currents increase nonlinearly with voltage.

High voltage (4 to 6 kV) partial discharge and leakage current measurements were performed on two HEDD 289HM TWTs (serial nos. 003 and 015). (The leakage currents were monitored by measuring the voltage drops across a resistor placed in series with the resonant detection circuit in Fig. 2.) In discharge testing of the gun section, both TWTs showed high frequency

($\approx 20,000/100$ sec), low magnitude (< 25 pC) discharges. Similar tests of the collector sections showed only sporadic low magnitude discharges. The leakage current measurements performed concurrently with the discharge measurements showed currents (I) that increased almost exponentially with voltage (V). To determine whether these I-V data would fit the I-V variation predicted for field emission from metals by the Fowler-Nordheim theory, plots of I/V^2 versus $1/V$ were drawn for I-V data obtained for serial no. 015. Fowler-Nordheim theory predicts that I-V data associated with field emission plotted in this way give a straight line with a negative slope when plotted on semilogarithmic paper (Ref. 7). In Fig. 7, both gun and collector leakage current show these characteristics, indicating both currents are produced by field emission. Field emission emanating from small surface irregularities may appear implausible at test voltages of only 4 to 6 kV; however, barium from the dispenser cathode used in these TWTs condensing on these surface irregularities can result in measurable currents even at these low voltages (Ref. 8). The discharges occurring at the same time as these leakage currents may just reflect the unstable behavior of these prebreakdown field emission currents.

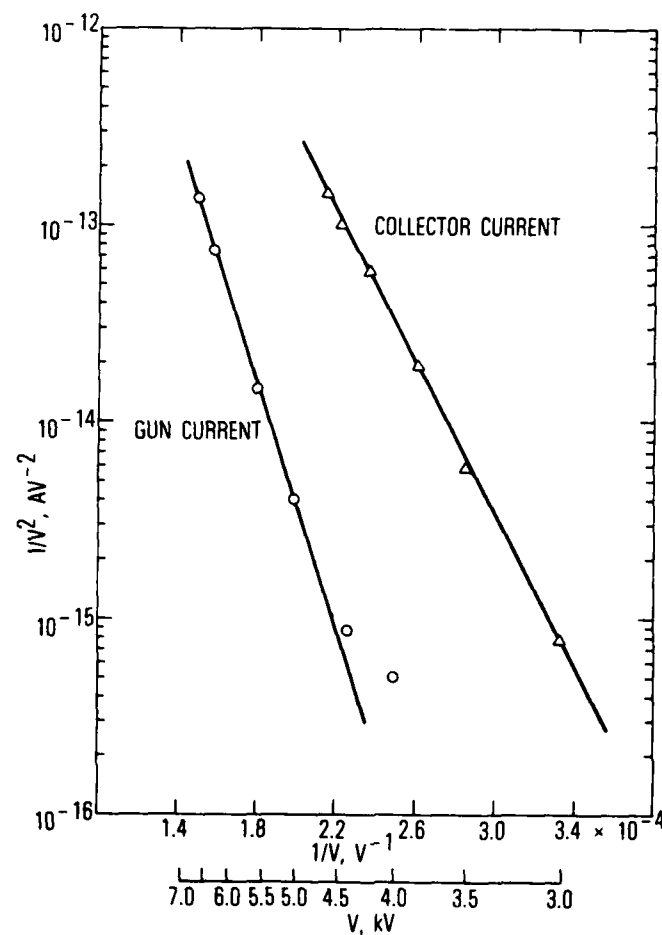


Fig. 7. Fowler-Nordheim Presentation of I-V Data for Serial No. 015

III. CONCLUSION

Partial discharge/environmental testing is effective in the screening of potted TWTs for space application. To enhance detection of cracks and voids in this type of HV insulation, discharge testing is being conducted under varying temperature and pressure conditions. Long-term partial discharge/environmental testing should be conducted on new or modified TWT models to eliminate generic defects. In the screening of all ceramic-vacuum insulated TWTs, leakage measurements, in addition to discharge measurements, must be performed.

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